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Diversity in Qualitative and Quantitative Traits Reveals Huge Potential for the Improvement of an Orphan Crop Tef [*Eragrostis tef* (Zucc.) Trotter]

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Authors' contributions

This work was carried out in collaboration among all authors. Author HJ designed the study, performed the statistical analysis, wrote the protocol and the first draft of the manuscript. Authors KA, KT, KD and ZT supervised the study. All authors read and approved the final manuscript.

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ABSTRACT

Aims: To assess the extent and pattern of genetic diversity in major qualitative and quantitative traits of tef accessions based on collection altitudes, and administrative regions and zones.
Study Design: Randomized complete Block Design with three replications.
Place and Duration of Study: The study was conducted at Debre Zeit and Holetta Research Centers in 2015 main cropping season.
Methodology: One hundred forty-four tef accessions collected from the Northern and Central Ethiopia were evaluated using five qualitative and seven quantitative traits. Microsoft Excel and Shannon-Weaver diversity index were used to determine the extent of genetic variations while

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cluster analysis based on the standardized data of various qualitative and quantitative traits was employed to group the accessions and collection altitudes, zones and regions.
Results: Yellowish white lemma, loose panicle, white seed, four internodes and green basal stalk were found to be the predominant phenotypic classes of the studied qualitative traits. The highest mean Shannon diversity was observed for panicle forms (0.396) followed by seed colour (0.370) while the lowest value was for basal stalk colour (0.083). Accessions from Oromia Regional State had the highest mean Shannon diversity and grain yield compared to the other two Regional States. Similarly, accessions from South Wello and West Shewa administrative zones had the highest mean Shannon diversity and highest grain yield, respectively. Besides, accessions from altitudes below 1500 m above sea level (a. s. l.) and from 2001 to 2500 m a. s. l. also had the highest mean diversity and highest mean grain yield, respectively. In cluster analysis, dendrogram constructed based on five qualitative and seven quantitative traits grouped the accessions, collection regions, zones and altitudes into six, two, four and three distinct clusters, respectively.
Conclusion: The present study generally revealed huge diversity among tef accessions collected from different regional states, administrative zones and altitudes which can be harnessed in future improvement of this understudied crop.

Keywords: Accessions, eragrostis tef; cluster analysis; genetic diversity; qualitative traits; quantitative traits; tef.

1. INTRODUCTION

Tef [*Eragrostis tef* (Zucc.) Trotter] is an indigenous cereal crop of Ethiopian known to have various nutritional, economic and ecological merits. It is a very useful source of human food and livestock feed. Tef adapts to a wide range of agro-ecologies, climate and soil conditions contributing for its wider wealth of genetic diversity. Despite its wider adaptation (from sea level to 3000 m a. s. l.), high preferences of both producers and consumers, and larger annual area coverage (> 3 million hectares) and grain production (> 5 million tons), the productivity of tef is extremely very low compared to the other cereals. Thus, its national average productivity is only 1.85 tons per hectare [1].

As tef is endemic to Ethiopia, the country is the primary source of its large and diverse germplasm resources. So far, nearly 6000 tef accessions from the major tef growing regions have been collected and deposited at the Ethiopian Biodiversity Institute (EBI). Due to the fact that tef is mainly cultivated in the middle and high elevations in Ethiopia, 82% of these germplasm was collected from the altitudes ranging from 1501 to 2500 m a. s. l. [2].

On the other hand, genetic diversity in indigenous breeds is a major concern considering the necessity of preserving what may be a precious and irreplaceable richness, regarding new productive demands [3,4]. Conservation should be based on a deep knowledge of the genetic resources of the specific breed [5,6]. Therefore, it is important to conduct the genetic characterization of indigenous breeds or species. The maintenance of genetic diversity in native species requires the adequate implementation of conservation priorities and sustainable management programs, which should be based on comprehensive information regarding the structure of the populations, including sources of genetic variability among and within breeds [7,8]. Genetic diversity is, therefore, an essential component for population survival, evolution, genetic improvement and adaptation to changing environmental conditions [9,10]. Molecular methods are useful tools to study the genetic variations [11,12]. Morphological markers, however, are the easiest and relatively the cheapest markers to assess the genetic diversity within and among populations. Especially when accessibility to modern tools is limited, they are extensively applied to document the diversity in phenotypic traits. Panicle form, seed and lemma color, embryo mark and basal stalk color are among the major morphological markers or parameters used to study the qualitative traits of tef [13,14]. Previous studies using different morphological markers revealed existence of considerable amount of variations in tef germplasms [15-20]. The first detailed characterization work on tef crop was conducted using 35 distinct cultivars based on both qualitative and quantitative traits [16]. The frequency of qualitative traits distribution over regions and altitudes, on the other hand, was also reported using germplasm collections from Western and Southern Ethiopia [20]. Using the same set of tef germplasm collection, [21] also reported existence of significant variations in major quantitative traits of tef. More recently, [22] studied tef germplasm collection from the Northern and Central Ethiopia and reported the existence of significant quantitative traits variation. However, studies conducted by [20,21] considered only tef germplasm from the southern and western Ethiopia while [22] who employed tef germplasm from Northern and Central Ethiopia reported the quantitative traits variations alone. Hence, very limited studies are available to report the qualitative and quantitative traits variation in tef germplasm from various regions of Ethiopia. The objective of this study was, therefore, to determine the extent and pattern of diversity in major qualitative and quantitative traits of tef germplasm based on altitudes, and administrative regions and zones of collections.

2. MATERIALS AND METHODS

2.1 Study Sites

The field evaluation was conducted at Holetta and Debre Zeit Agricultural Research Centers in Ethiopia during the main cropping season of 2015.Holetta Research Center is located 39 km west of Addis Ababa at $9^0$44’ N, $38^0$30’ E and at an altitude of 2400 m a. s. l. While the mean annual rainfall of the site is 1100 mm, the annual minimum and maximum temperatures are 6^0C and 22^0C, respectively [23]. Debre Zeit Agricultural Research Center, which is located 47 km East of Addis Ababa is situated at 8^0 44'N and $38^0$58'E and at an altitude of 1900 m. a. s. l. This site receives a mean annual rainfall of 851 mm with minimum and maximum temperature of 8.9^0C and 28.3^0C, respectively [23]. The soils at the experimental site were acidic Nitosols at Holetta and a Pellic Vertisol with high moisture holding capacity at Debre Zeit.

2.2 Plant Materials and Experimental Design

One hundred forty-four tef accessions collected from 12 administrative zones of Amhara, Oromia and Tigray Regional States by EBI between 1979 and 2011 from altitude range of 1260 m to 3090 m a. s. l. were studied. Table 1 presents the details on the regional states, administrative zones and altitudes of collection. The design was randomized complete block design with three replications. Two rows of 0.5 m length was used for each genotype at spacing of 0.2 m, 0.4m and 1.5m between genotypes, rows and replications, respectively. All agronomic and cultural practices recommended for tef production at each location were applied.

2.3 Data Collection and Analysis

Qualitative traits data such as panicle form, number of internodes, and color of basal stalk culm, lemma and seeds according to earlier studies were recorded [13,24]. Microsoft Excel was used to analyze the qualitative traits while the extent of genetic variations was determined using Shannon-Weaver diversity index [25] as follows:

$$\mathrm{H}' = -\sum_{i=1}^{n} Pi\ log\ ePi$$

Where n is the number of phenotypic classes for a character and Pi is the genotypic frequency as the percentage proportion of the total entries in the i^{th} class. The diversity index was estimated at the regional, zonal and altitudinal levels.

In addition to the qualitative traits, data were also collected on seven quantitative traits such as days to maturity, peduncle length, culm diameter, number of spikelets per panicle, grain and biomass yield, lodging percentage. Cluster analysis at regional, zonal and altitudinal levels were conducted based on standardized data of the five qualitative and seven quantitative traits using MINITAB software version 17.1 [26]. Besides, Dendrogram for individual accessions was constructed using PAST software [27] and edited for visualization using Fig-Tree software version 1.4.3 [28].

3. RESULTS AND DISCUSSION

3.1 Observed Phenotypic Classes of Key Qualitative Traits in Tef

Each of the five qualitative traits investigated in this study showed 3 to 5 phenotypic classes (Table 2). The observed five traits and their corresponding phenotypic classes were variegated, yellowish white, purple, red and green lemma colour; very loose, loose, fairly loose, semi compact and compact panicle forms; dark brown, golden brown, green and purple basal stalk colour; brown, white and very white seed colour; and three, four and five number of internodes. Thus, our findings revealed existence of considerable range of variations in qualitative traits such as panicle form, and the colour of grain, lemma and stalk. Likewise, previous studies identified panicle form, and colour of grain, lemma and stalk as the most important traits to distinguish among various qualitative traits of tef genotypes [13,17,29,30].

3.2 Distribution of Phenotypic Classes of Tef Qualitative Traits

Table 3 presents the proportions of phenotypic classes of the five qualitative traits in the present study. To begin with, panicle form is the most important qualitative trait to determine the productivity of a given tef accession. Based on regional states and administrative zones of collection, loose panicle type was the dominant type accounting for 48.6% followed by the fairly loose (32.6%) and very loose (13.9%) panicle. Tef accessions with compact and semi-compact panicle type, on the other hand, constituted less than 5% of the studied accessions. Among the very loose, loose and fairly loose panicle types, the latter two were found to be very dominant in all administrative zones other than West Gojam, North Shewa and West Shewa where accessions with loose, fairly loose and very loose panicle form have equal proportion. Panicle forms showed similar trend for collection altitudes, administrative zones and regional states with the loose and fairly loose type together accounting for over 80% of the entire panicle forms.

According to [17] tef genotypes with loose panicle forms are early maturing, adapted to wider agro-ecologies and give higher yield compared to those with compact panicle type. In our present study, the loose and fairly loose panicle forms were found to account for the lion share in almost all zones of collections. This is, therefore, a good opportunity to make selection for traits related to grain yield, earliness and adaptation to moisture deficit environmental condition [13,24,30]. The early maturing accessions, on the other hand, are useful to address climate change related problems and for double cropping to increase the productivity of tef in our country. The compact panicle form, however, had the lowest representation in all collection regions, zones and altitudes may be due to human selection against compact panicle form while seeking for the higher yielding loose panicle forms [17].

The distribution of various classes of lemma colour over regional states, administrative zones and altitudes are presented in Table 3. The yellowish white (42.4%) and variegated (36.8%) lemma colour represented the major phenotypic class while all the remaining classes together accounted for only about 20% of the variation. Regarding collection zones, germplasm from Central Tigray (66.7%), North Shewa (50.0%), South Wello (58.3%) and West Gojam (50%) zones had variegated lemma unlike the remaining zones, which had yellowish white lemma colour. The majority of germplasm accessions in all collection regions, on the other hand, exhibited yellowish white followed by variegated lemma colour. Furthermore, variegated lemma colour was the predominant phenotypic classes in all altitudes except for elevation ranging from 2001 to 2500 m a. s. l. where yellowish white colour was dominant.

The percentage distribution of seed colour, number of internodes and basal stalk colour among collection zones, regions and altitudes are summarized (Table 3). The green basal stalk colour accounted for about 90% of the phenotypic classes while the other three colours together constituted less than 10% of the variation. Similar trends of basal stalk colour were observed for all collection zones, regions and altitudes. Golden brown colored stalks were found to exist among accession from North Gonder, South Wello and North Shewa zones while dark brown existed among accessions from West Tigray, South Gonder and West Shewa. Similarly, West Tigray, South Gonder and North Shewa zones had purple basal stalk colour. In the present study, accessions from Tigray region and lower altitude (< 1500 m) had no golden-brown stalk while those from below 1500m and between 2001 and 2500 m had no dark brown basal stalk colour. Similarly, accessions from altitude ranging from 1501 m to 2000 m and above 2500 m a. s. l. had no purple basal stalk.

Majority of the studied accessions had four internodes (56.3%) followed by three internodes (41.7%) while nearly 2% had five internodes. Besides, 44.4%, 43.8% and 11.8% of the studied germplasm lines had white, brown and very white grain colour, respectively. In general, most accessions from Central, East and West Tigray, West Gojam and West Shewa Zones exhibited white seed colour while those from North and South Gonder, North and South Wello, East Gojam and North Shewa had brown seed colour. The majority of tef accessions from East Shewa zone, on the other hand, exhibited very white seed colour (Table 3). Such larger proportion of very white seed colour in East Shewa could be a justification for the premium market price given for tef grain from the indicated Zone [31]. Regarding altitudes of collection, the proportion of brown seed colour markedly increased with an increase in altitude above 2500m while the white and very white seed classes decreased dramatically. In other words, accessions with brown seed colour accounted for the lion share at higher altitude showing the influence of altitude on seed colour showing that the brown seeded accessions are the most adapted to the higher elevation compared to the white or very white coloured accessions. To summarize it, the yellowish and variegated lemma, loose panicle, white followed by brown seed colour, four internodes and green basal stalk were the major phenotypic classes of tef qualitative traits over all collection regions, zones and altitudes in the present study.

3.3 Shannon-Weaver Diversity Index (H')

The results of Shannon diversity for germplasm collection zones, regions and altitudes are summarized in Table 4. South Wello zone had the highest Shannon diversity index (0.468) for seed colour unlike those from East Tigray (0.276), West Tigray (0.276) and South Gonder (0.276) zones. The diversity for panicle form, on the other hand, ranged from 0.295 for South Gonder to 0.469 for West Shewa zone while those for lemma colour ranged from 0.247 (East Shewa) to 0.439 (West Tigray). Surprisingly, about half of the administrative zones had the lowest Shannon diversity indices for basal stalk colour whereas, number of culm internodes ranged from 0.244 for South Gonder and North Shewa to 0.439 for East Tigray. Among all studied traits, the highest mean diversity was for panicle form (0.396) followed by seed colour (0.370) while basal stalk colour had the lowest mean diversity (0.083). Combined mean diversity for the five qualitative traits, on the other hand, ranged from 0.262 for Central Tigray to 0.373 for South Wello zone (Table 4).

The Shannon diversity indices among the three collection regions ranged from 0.318 (Tigray) to 0.464 (Oromia) for seed colour, from 0.419 (Tigray) to 0.443 (Oromia) for panicle form, from 0.345 (Amhara) to 0.382 (Tigray) for lemma colour, from 0.161 (Amhara) to 0.179 (Tigray) for basal stalk colour and from 0.298 (Tigray) to 0.348 (Oromia) for number of internodes. Among the three regional states, Oromia had the highest mean Shannon diversity (0.356) (Table 4).

The Shannon diversity indices over the four altitudes ranged from 0.330 to 0.453 for seed colour, 0.349 to 0.463 for panicle form, 0.381 to 0.407 for lemma colour, 0.078 to 0.273 for basal stalk colour and from 0.298 to 0.352. Thus, altitude below 1500m had the highest mean Shannon diversity (0.371) while the lowest was for altitude above 2500m (0.304) (Table 4).

3.4 Cluster Analysis

3.4.1 Clustering of individual tef accessions

Cluster analysis grouped the 144 tef accessions into six distinct clusters each with 11 to 32 accessions based on standardized data of five qualitative and seven major quantitative traits (Fig. 1). Thus, cluster I consisted of 11 accessions from West Gojam (7), South Wello (2), South Gonder (1) and West Shewa (1) administrative zones. Most accessions in this cluster had brown seed colour, loose panicle, dark brown basal stalk, red lemma and three internodes but with the highest lodging percentage, lowest number of spikelets per panicle and the thinnest culm diameter. Cluster-II, on the other hand, consisted of 28 accessions from all zones except West Gojam. White seed colour, loose panicle, green basal stalk, variegated lemma and three internodes along with the shortest days to heading and peduncle length were the typical features of accessions in Cluster-II. Cluster III consisted of 31 accessions from all zones except North Wello. Most the accessions in cluster III were from East Tigray (5), South Gonder (5) and South Wello (5). Cluster IV consisted of 32 accessions from all zones other than East Gojam. Besides, accessions in this cluster were mostly represented by white seed colour, fairly loose panicle, green basal stalk, variegated lemma colour and four internodes along with the smallest grain yield and the longest peduncle length. Cluster V consisted of 30 accessions from all zones except East Shewa. Most of the accessions in Cluster V were collections from South Wello (7) and East Tigray (4). Brown seed colour, loose panicle form, golden brown stalk, variegated lemma colour, four internodes and the longest days to maturity were the major distinguishing features of accessions in this cluster. Cluster VI consisted of 12 accessions mainly from East Gojam (3), East Shewa (2), North Gonder (2) and West Shewa (2). The major features of accessions in cluster VI were brown seed, green stalk and lemma loose panicle and four internodes along with relatively larger culm diameter and number of spikelets per panicle (Table 5).

Table 1. Names of tef accessions used in the present study and sites of their collections

Site: Regional state	Site: Administrative zone	Number of accessions	Name of the studied tef accessions	Altitude (m a. s. l)
Tigray	Central Tigray	12	Acc. nos. 19132-2, 19132-3, 19166-1,19253-1,19253-2, 234407-1, 234407-2, 237184-1, 237205-2, 243513-1, 243513-3 & 243520-2	1350-2640
	East Tigray	12	Acc. nos. 15297-1, 15297-2,15299-1,15299-3,19201-1,19201-3, 19202-2, 234460-1, 234460-2, 234460-3, 242540-1 and 242540-2	1979-2632
	West Tigray	12	Acc. nos. 9419-1, 9444-2, 9444-3, 19241-1, 19241-2, 234435-2, 237236-3, 237236-4, 237239-3, 243526-2, 243526-4 and 243526-5	1260-2054
Amhara	East Gojam	12	Acc. nos. 9545-1, 9556-1, 19516-1, 19516-3, 55221-1, 55221-2, 212698-2, 229768-1, 229768-3, 229768-4, 55046-2 and 55046-3	1470-2650
	West Gojam	12	Acc. nos. 19394-1, 19443-3, 19452-4, 19506-2, 19506-4, 242140-3, 242144-1, 242144-3, 242155-1, 242155-3, 55029-2 and 55029-3	1890-2735
	North Gonder	12	Acc.9448-1, 9448-2, 9451-2, 9469-2, 9472-2, 9472-4,19343-2, 242186-3, 242186-4, 243540-1, 243540-3 and 243540-4	1840-2208
	North Wello	12	Acc. nos. 55104-3, 215196-1, 215200-1, 215200-2, 215200-3, 234356-4, 234985-2, 234993-1, 234993-3, 237148-1, 237148-5 and 243501-2	1520-2950
	South Gonder	12	Acc. nos. 19341-2, 19341-3, 19367-2, 19374-1, 55293-2, 212717-0, 212720-1, 225919-2, 225919-3, 225919-4, 225919-7 and 242160-1	1804-2950
	South Wello	12	Acc. nos. 212607-2, 212612-3, 212614-1, 212614-2, 225898-1, 242214-1, 242214-2, 243491-2, 2433497-2, 243504-1, 243504-2 and 243504-3	1550-3090
Oromia	East Shewa	12	Acc. nos. 15361-3, 17335-1, 18460-0, 18466-2, 18466-3, 236963-1, 236963-2, 236965-1,236965-3,236967-1, 236967-2 and 236972-0	1657-2303
	North Shewa	12	Acc. nos. 9559-1, 9559-2, 15309-2, 15309-3, 15322-1, 15322-2, 18385-2, 212482-1, 236745-2, 236746-0, 236748-2 and 236957-1	1260-2670
	West Shewa	12	Acc. nos. 17365-1, 17371-3, 18410-1, 18410-2, 18410-3,18414-2, 18414-4, 18423-3, 236757-2, 236760-1, 236760-4 and 236760-6	1640-2674

Table 2. Name and phenotypic classes of five qualitative traits

Trait	Phenotypic classes	
	Number	**Name**
Lemma colour	5	Green, purple, Red, Variegated, Yellowish white
Panicle form	5	Very loose, Loose, Fairly loose, Semi compact, Compact
Basal stalk color	4	Dark brown, Golden brown, Green, purple
Seed colour	3	Brown, White, Very white
Number of internodes	3	Three, Four, Five

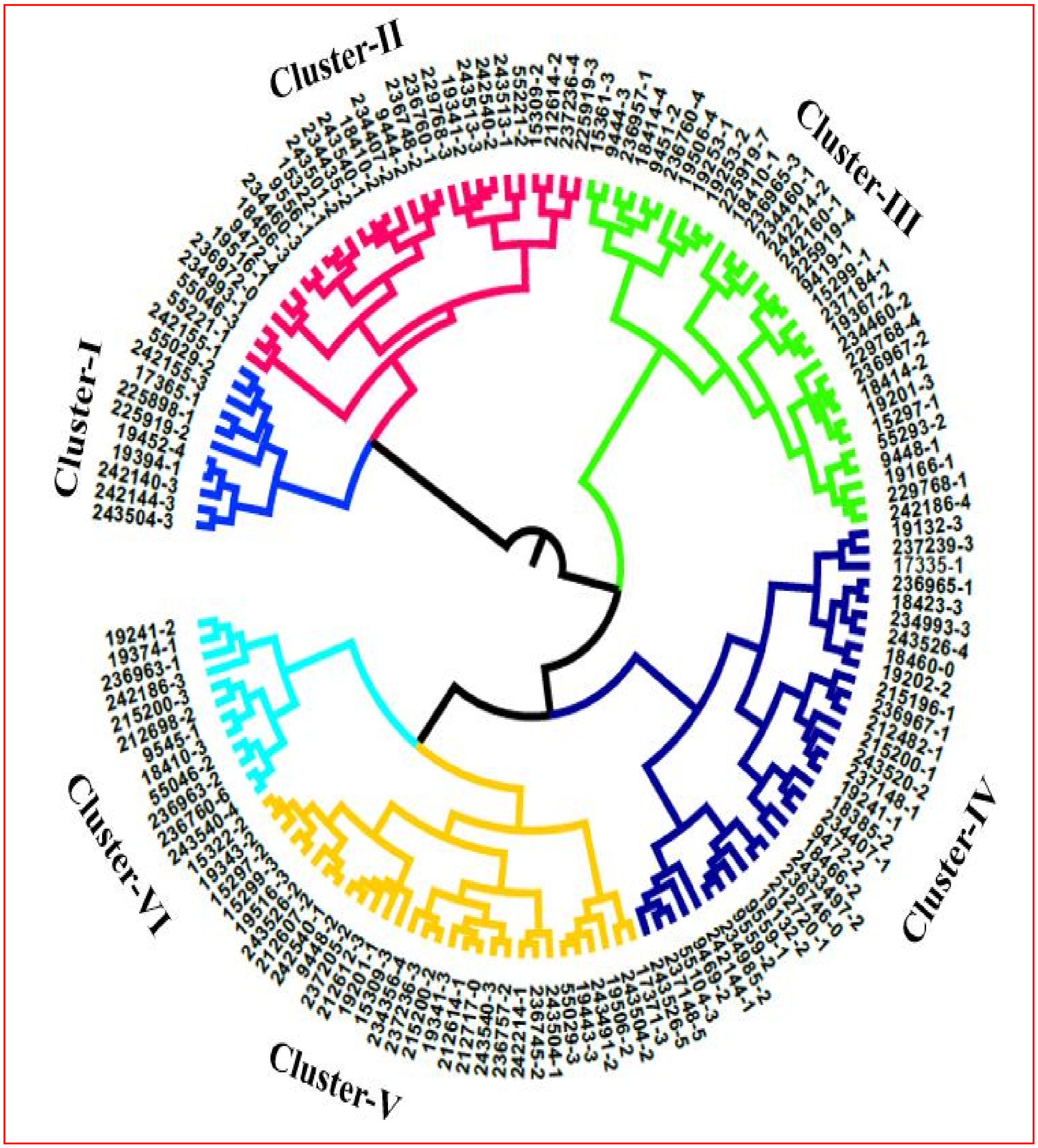

Fig. 1. Dendrogram showing the genetic relationship among 144 tef accessions from 12 administrative zones in North and Central Ethiopia based on five qualitative and seven quantitative traits

Table 3. The proportion of phenotypic classes (%) for lemma colour, panicle form, seed colour, number of internodes and basal stalk colour of 144 tef accessions by collection zones, regions and altitudes

Germplasm sources		Panicle form				Lemma colour					
		Loose	**FL**	**SC**	**Comp**	**Variegated**	**YW**	**Purple**	**Red**	**Green**	**VL**
Zones	Central Tigray	50.0	33.3	8.3	0.0	66.7	33.3	0.0	0.0	0.0	8.3
	East Tigray	58.3	8.3	0.0	16.7	33.3	66.7	0.0	0.0	0.0	16.7
	West Tigray	33.3	58.3	0.0	0.0	25.0	41.7	16.7	8.3	8.3	8.3
	North Gonder	50.0	33.3	0.0	0.0	33.3	41.7	0.0	8.3	16.7	16.7
	South Gonder	58.3	41.7	0.0	0.0	25.0	50.0	0.0	16.7	8.3	0.0
	North Wello	41.7	41.7	0.0	8.3	50.0	33.3	0.0	16.7	0.0	8.3
	South Wello	58.3	33.3	0.0	0.0	25.0	41.7	8.3	25.0	0.0	8.3
	East Gojam	58.3	8.3	0.0	16.7	25.0	41.7	0.0	8.3	25.0	16.7
	West Gojam	25.0	50.0	0.0	0.0	58.3	25.0	0.0	0	16.7	25.0
	North Shewa	50.0	25.0	0.0	0.0	50.0	33.3	0.0	16.7	0.0	25.0
	East Shewa	66.7	25.0	0.0	0.0	16.7	66.7	0.0	0.0	16.7	8.3
	West Shewa	33.3	33.3	0.0	8.3	33.3	33.3	8.3	0.0	25.0	25.0
	Mean	48.6	32.6	0.69	4.17	36.8	42.4	2.8	8.3	9.7	13.9
Regions	Tigray	47.2	33.3	2.8	5.6	41.7	47.2	5.6	2.8	2.8	11.1
	Amhara	48.6	34.7	0.0	4.2	36.11	38.9	13.9	12.5	11.1	12.5
	Oromia	50.0	27.8	0.0	2.8	33.3	44.4	2.8	5.6	13.9	19.4
	Mean	48.6	32.6	0.69	4.17	36.8	42.4	2.8	8.3	9.7	13.9
Altitudes	<1500	41.7	41.7	0.0	0.0	50	25	8.3	16.7	0.0	16.7
	1501-2000	59.2	30.6	2.0	4.1	40.8	36.7	8.2	4.1	10.2	4.1
	2001-2500	39.2	35.3	0.0	0.0	37.3	41.2	5.9	0.0	15.7	25.5
	>2500m	53.1	34.2	0.0	6.3	53.1	34.2	6.3	0.0	6.3	6.3
	Mean	49.3	34.0	0.69	2.8	43.1	36.8	6.9	2.42	10.4	13.2

Abbreviations: Comp= Compact, FL= Fairly loose, SC= Semi compact, VL= very loose, YW = Yellowish white

Table 3. continued

Germplasm sources		Seed colour (%)			Number of internodes (%)			Basal stalk colour (%)			
		Brown	White	VW	Three	Four	Five	GB	DB	Purple	Green
Zones	Central Tigray	25.0	66.7	8.3	66.7	33.3	0.0	0.0	0.0	0.0	100
	East Tigray	33.3	66.7	0.0	50.0	33.3	16.7	0.0	0.0	0.0	100
	West Tigray	33.3	66.7	0.0	66.7	33.3	0.0	0.0	33.3	8.3	66.7
	North Gonder	58.3	33.3	8.3	33.3	66.7	0.0	8.3	0.0	0.0	91.7
	South Gonder	66.7	33.3	0.0	25.0	75.0	0.0	0.0	8.3	8.3	83.3
	North Wello	50.0	41.7	8.3	50.0	50.0	0.0	0.0	0.0	0.0	100
	South Wello	41.7	33.3	25.0	50.0	50.0	0.0	8.3	16.7	0.0	75.0
	East Gojam	58.3	(33.3	8.3	33.3	66.7	0.0	0.0	0.0	0.0	100
	West Gojam	25.0	66.7	8.3	33.3	66.7	0.0	0.0	0.0	0.0	100
	North Shewa	58.3	25.0	16.7	25.0	75.0	0.0	8.3	0.0	8.3	83.3
	East Shewa	33.3	16.7	50.0	33.3	58.3	8.3	0.0	0.0	0.0	100
	West Shewa	41.7	50.0	8.3	33.3	66.7	0.0	0.0	8.3	0.0	91.7
	Mean	43.8	44.4	11.8	41.7	56.3	2.1	2.1	4.9	2.1	91.0
Regions	Tigray	30.6	66.7	2.8	61.1	33.3	5.6	0.0	8.3	2.8	88.9
	Amhara	50.0	40.3	9.7	37.5	62.5	0.0	2.8	4.2	1.4	91.7
	Oromia	44.4	30.6	25.0	30.6	66.7	2.8	2.8	2.8	2.8	91.7
	Mean	43.8	44.4	11.8	41.7	56.3	2.1	2.1	4.9	2.1	90.9
Altitudes	<1500	41.7	41.7	16.7	16.7	76.9	8.3	23.1	0.0	8.3	66.7
	1501-2000	40.8	40.8	18.4	40.8	57.1	2.0	6.1	2.0	0 .0	91.8
	2001-2500	39.2	51.0	9.8	44	56	0.0	2.0	0.0	3.9	94.1
	>2500m	56.3	37.5	6.3	50	4.7	3.1	0.0	6.3	0.0	93.8
	Mean	43.1	43.8	12.5	41.7	56.3	2.1	4.9	2.1	2.1	91

Abbreviations: VW = Very white, GB= Golden brown, DB= Dark brown

Table 4. Shannon diversity indices (H') of five qualitative traits for 144 tef accessions collected from three regional states and 12 administrative zones in Ethiopia

Category		Qualitative traits					
		SC	**PF**	**LC**	**BSC**	**NI**	**Mean + SE**
Zones	Central Tigray	0.358	0.399	0.276	0.000	0.276	0.262±0.070
	East Tigray	0.276	0.356	0.276	0.000	0.439	0.269±0.074
	West Tigray	0.276	0.386	0.439	0.117	0.276	0.299±0.055
	North Gonder	0.386	0.439	0.317	0.035	0.276	0.291±0.070
	South Gonder	0.276	0.295	0.301	0.246	0.244	0.272±0.012
	North Wello	0.399	0.407	0.31	0.000	0.301	0.283±0.074
	South Wello	0.468	0.386	0.399	0.313	0.301	0.373±0.031
	East Gojam	0.386	0.356	0.309	0.000	0.276	0.265±0.069
	West Gojam	0.358	0.452	0.287	0.000	0.276	0.275±0.075
	North Shewa	0.417	0.452	0.310	0.246	0.244	0.334±0.043
	East Shewa	0.440	0.358	0.247	0.000	0.386	0.286±0.078
	West Shewa	0.399	0.469	0.408	0.035	0.276	0.317±0.077
	Mean	0.370	0.396	0.323	0.083	0.298	0.294±0.056
Regions	Tigray	0.318	0.419	0.382	0.179	0.298	0.319±0.041
	Amhara	0.408	0.425	0.345	0.161	0.334	0.335±0.047
	Oromia	0.464	0.443	0.359	0.164	0.348	0.356±0.053
	Mean	0.397	0.429	0.362	0.168	0.327	0.336±0.045
Altitudes	<1500	0.447	0.447	0.391	0.273	0.298	0.371±0.041
	501-2000	0.453	0.349	0.407	0.115	0.332	0.331±0.065
	2001-2500	0.407	0.463	0.391	0.093	0.298	0.330±0.073
	>2500	0.330	0.381	0.381	0.078	0.352	0.304±0.064
	Mean	0.409	0.410	0.393	0.140	0.320	0.334±0.057

Abbreviations: SC = seed colour, PF = panicle form, LC = lemma colour, BSC = basal stalk colour, NI = number of culm internodes; SE = standard error

In this study, 2 to 6 number of clusters were formed for accessions, zones, regions and altitudes of collections. Clustering based on individual accessions, for instance, revealed the formation of six clusters in the present study. Similar numbers of clusters were reported from earlier studies on tef [19,22,32,33,34]. In the present study, the grouping of individual accession was not solely based on collection regions, zones and altitudes. Thus, accessions from different collection zones, regions and altitudes were grouped into the same cluster may be due to various factors. A good example is a situation where accession from three Shewa administrative zones of Oromia region were grouped into three different clusters, and those from the three zones of Tigray region were grouped into two different clusters along with those from other regions. Such grouping of accessions from the same regions into different clusters could be due to seed movement mediated by humans far beyond borders. Unlike this grouping, accessions from North and South Wello zones and East and West Gojam zones of Amhara regional state were grouped together into cluster I and II, respectively maybe due to free exchange of germplasm along their borders.

Analysis of cluster mean enabled us to identify clusters consisting of accessions with traits of interest for future tef breeding (Table 5). Accessions in Cluster-I, for instance, were known to have thinner culm diameter and lower number of spikelets per panicle while those in cluster-II had the shortest days to maturity and peduncle length. The accessions in cluster-II are, therefore, useful to screen for earliness so as to be used for moisture stress areas and for double cropping. Accessions in cluster-III, on the other hand, exhibited the largest yield of grain and biomass unlike those in cluster -IV which had the lowest grain yield and the longest peduncle. Cluster VI consisted of accessions with the highest culm diameter and number of spikelets per panicle. It is, therefore, possible to screen for higher yield among germplasm in cluster-III and VI.

3.4.2 Clustering based on administrative zones of collection

Clustering of 12 administrative zones of collections based on five qualitative and seven quantitative traits of tef revealed the formation of four distinct clusters (Fig. 2). The number of zones grouped under cluster I, II and IV were six, three and two, respectively while cluster III remained solitary and consisted of East Shewa zone alone. Thus, Central Tigray, North Wello, East Tigray, North Shewa, South Gonder and South Wello zones were grouped under Cluster-I unlike Cluster II which consisted of East Gojam and West Gojam zones. On the other hand, North Gonder, West Shewa and West Tigray were grouped under Cluster-IV. In this clustering, most of the adjacent zones like East and West Gojam, North Gondar and West Tigray, East and Central Tigray, respectively were found to appear together in the same group may be due to sharing of similar germplasm along their borders.

Based on cluster mean of collection zones (Table 6), it was possible to identify zones consisting of accession with potentially useful traits. Cluster-III, for instance, consisted of a single zone which had accessions with the highest grain yield, days to maturity, peduncle length, culm diameter and number of spikelets per panicle showing the possibility of obtaining high yielding genotypes from this administrative zone. Cluster-II, on the other hand, consisted of Zones having accessions with the lowest days to maturity, culm diameter and number of spikelets per panicle showing the possibility of selecting for early maturing genotypes among the accessions in this particular cluster.

3.4.3 Clustering based on collection altitudes and regional states

Clustering of the four altitudes of collections based on five qualitative and seven quantitative traits of tef resulted in the formation of three distinct clusters (Fig. 3). Thus, cluster I consisted of altitudes below 1500m and between 1501 and 2000m while cluster-II and III remained solitary and consisted of altitude between 2001 and 2500m, and above 2500 m a. s. l., respectively. Clustering of Regional States, on the other hand, grouped Tigray and Amhara regions together into Cluster-I while Oromia regional states remained solitary and became alone (Fig. 4). Cluster mean of collection altitudes revealed that accession from altitude between 1500 and 2500 m. a. s. l. (those in cluster-II) had the highest yield of grain and biomass, and number of spikelets per panicle showing the possibility to identify high yielding genotypes among collection from this altitude. Cluster- III, consisted of accessions from high altitude (> 2500 m) which had the longest days to maturity and peduncle length unlike cluster -I which are from the lower altitude (< 1500 m) and had the thinnest culm diameter (Table 7).

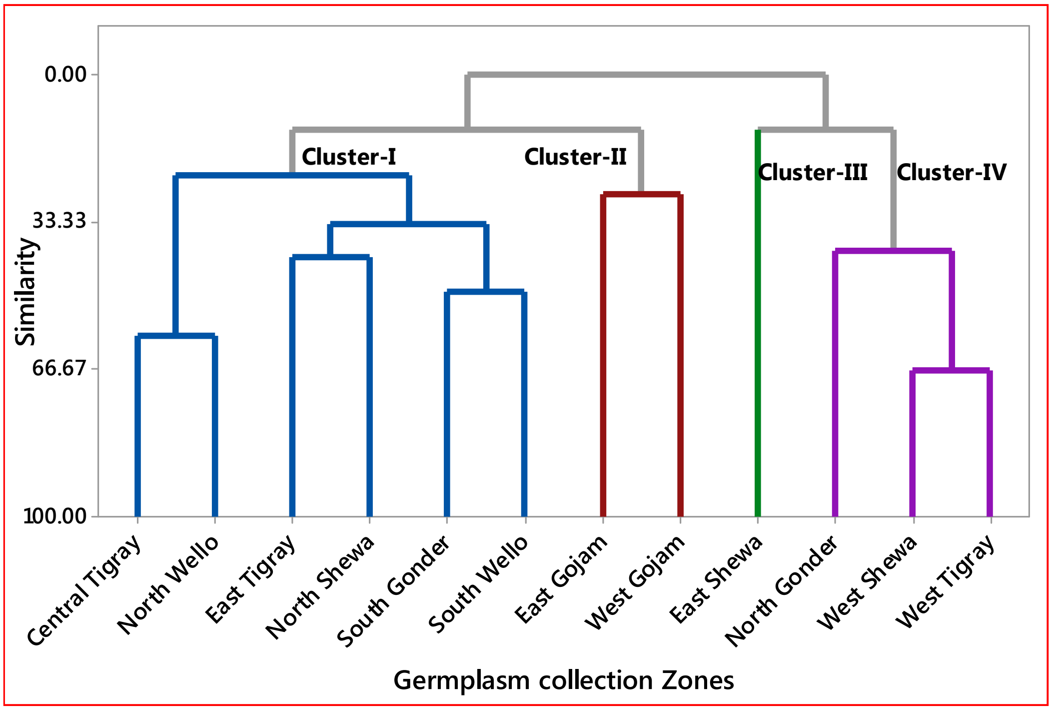

Fig. 2. Dendrogram showing the clustering patterns of 12 zones of germplasm collections based on variation in five qualitative and seven quantitative traits of tef

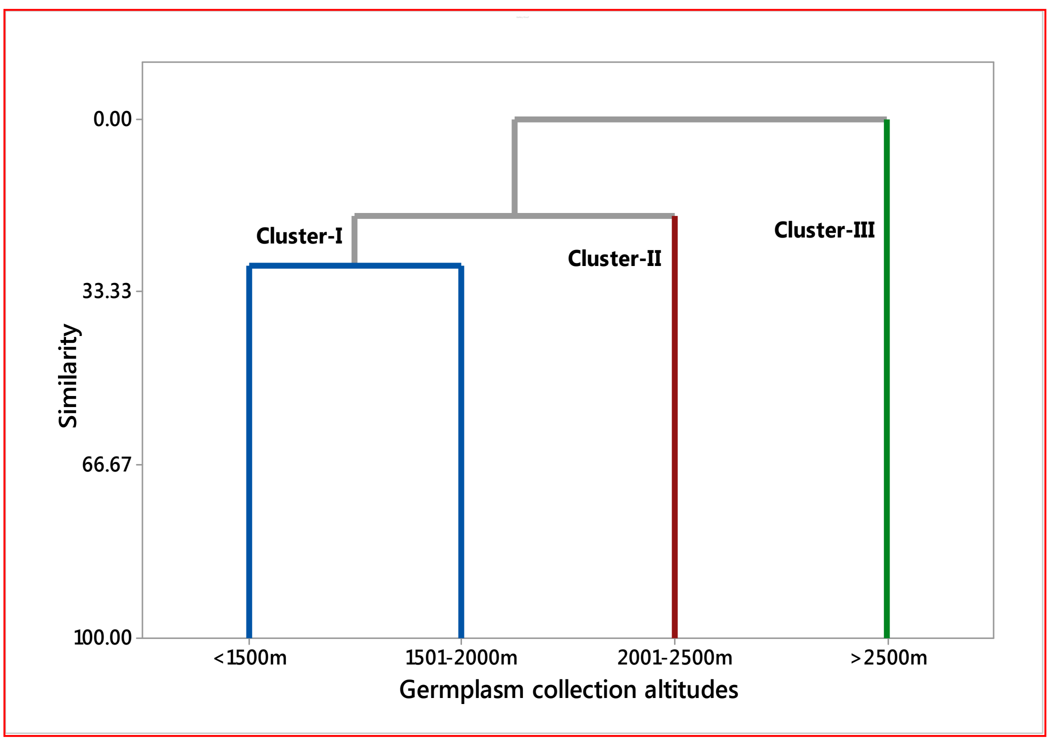

Fig. 3. Dendrogram showing clustering pattern among four altitudes of germplasm collections based on five qualitative and seven quantitative traits of tef

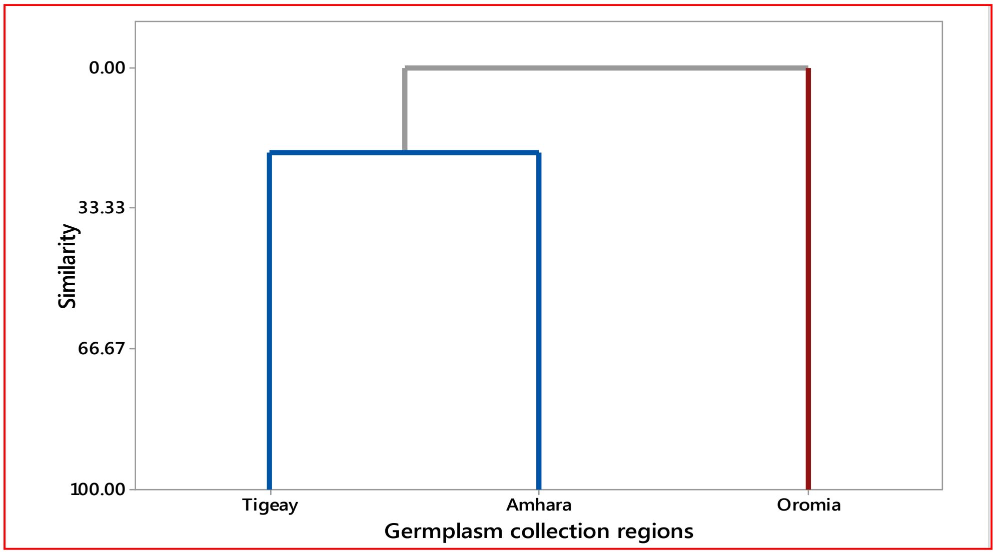

Fig. 4. Dendrogram showing clustering pattern among three regions of germplasm collections based on five qualitative and seven quantitative traits of tef

Table 5. Cluster means of five qualitative and seven quantitative traits of 144 tef germplasm lines

Traits	Cluster mean					
	I	II	III	IV	V	VI
Seed colour	1.50	1.55	2.00	1.97	1.43	1.08
Panicle form	2.20	2.45	2.32	2.56	2.10	1.83
Basal stalk colour	1.30	2.97	2.87	2.78	2.43	2.83
Lemma colour	3.30	3.86	4.45	4.38	4.00	1.42
Internode number	3.20	3.48	3.32	3.72	4.03	3.58
Biomass yield	24.59	25.26	30.38	24.9	26.05	28.27
Grain yield	5.44	5.65	6.19	5.1	5.34	5.95
Days to maturity	109.96	109.64	115.15	115.9	115.94	114.75
Peduncle length	18.55	17.65	18.47	20.1	18.92	19.18
Culm diameter	1.35	1.39	1.55	1.6	1.53	1.64
Spikelets per panicle (number)	248.92	262.30	334.75	304.9	321.12	354.90
Lodging percentage	71.17	69.48	68.59	62.9	68.99	67.47

Table 6. Cluster means of five qualitative and seven quantitative traits of tef from 12 zones of collections

Traits	Cluster mean			
	I	II	III	IV
Seed colour	1.61	1.67	2.17	1.64
Panicle form	2.31	2.33	2.17	2.33
Basal stalk colour	2.79	2.00	3.00	2.75
Lemma colour	4.13	3.71	3.67	3.61
Internode number	3.57	3.50	3.50	3.78
Biomass yield	26.00	26.48	26.73	28.07
Grain yield	5.49	5.59	5.83	5.70
Days to maturity	114.22	112.15	114.58	114.48
Peduncle length	19.21	18.42	19.29	18.19
Culm diameter	1.52	1.48	1.64	1.53
Spikelets per panicle (number)	300.18	287.36	337.65	321.15
Lodging percentage	67.30	69.75	66.76	67.33

Table 7. Cluster means of five qualitative and seven quantitative traits of tef from four altitudes and three regions germplasm collections

Traits	Altitudinal cluster mean			Regional state cluster mean	
	I	II	III	I	II
Seed colour	1.75	1.76	1.71	1.47	1.72
Panicle form	2.25	2.43	2.10	2.47	2.36
Basal stalk colour	2.83	2.78	2.55	2.63	2.94
Lemma colour	3.92	3.86	3.82	4.03	4.22
Internode number	3.67	3.57	3.59	3.66	3.61
Biomass yield	26.76	27.20	27.21	24.90	27.23
Grain yield	5.51	5.56	5.72	5.47	5.59
Days to maturity	113.96	114.10	113.83	114.00	114.24
Peduncle length	17.60	18.63	18.80	19.65	18.51
Culm diameter	1.52	1.53	1.53	1.53	1.54
Spikelet per panicle (number)	310.48	313.41	309.20	289.71	298.85
Lodging percentage	68.21	67.23	67.86	67.84	67.71

4. CONCLUSION

The present study which dealt with the assessment of both qualitative and quantitative traits of tef accessions collected from the northern and central parts of Ethiopia showed how these traits vary with collection altitudes, administrative zones and regional states. For instance, brown seed colour was the dominant phenotypic class at higher altitudes while the very white seeded accessions accounted for about 50% in East Shewa collection. On the other hand, some phenotypic classes of a given qualitative traits were also found to be common in all regions, zones and altitudes of collections while others are unique to specific zones or altitudes. In general, the present study enabled to identify regional states, administrative zones and altitudes harboring potentially useful traits for future consideration.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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